

Undoubtable signs of CP-violation in Higgs decays at the LHC run 2

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Abstract

With the discovery of the Higgs boson at the Large Hadron Collider the high energy physics community's attention has now turned to understanding the properties of the Higgs boson, together with the hope of finding more scalars during run 2. In this work we discuss scenarios where using a combination of three decays, involving the 125 GeV Higgs boson, the Z boson and at least one more scalar, an indisputable signal of CP-violation arises.

We use a complex two-Higgs doublet model as a reference model and present some benchmark points that have passed all current experimental and theoretical constraints, and that have cross sections large enough to be probed during run 2.

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1 Introduction

The discovery of the Higgs boson by the ATLAS [1] and CMS [2] collaborations at the Large Hadron Collider (LHC) has raised the interest of the high energy physics community in multi-scalar models. One of the most attractive features of some of these models is to provide extra sources of CP-violation which could help to explain the matter anti-matter asymmetry of the Universe. This was the reason that lead T.D. Lee to propose the two-Higgs double model (2HDM) [3] as a means to explain this asymmetry. Reviews of the 2HDM may be found, for example, in [4, 5]. One of the CP-violating complex versions of the 2HDM, which we refer to as C2HDM, has been the subject of many recent studies [6–12]. The C2HDM was first proposed in [13] and it is the simplest version of an explicit CP-violating 2HDM with a clear and easy limit leading to its CP-conserving version.

As proposed in [14], CP-violation in the scalar sector can be found in the interactions with gauge bosons in a very simple way. If CP were conserved, any decay $h_i \rightarrow h_j Z$ would imply opposite CP parities for h_i and h_j . Moreover, assuming only lagrangian terms up to dimension four, any scalar h_i decaying into ZZ would be CP even ¹. Thus, for example, the simultaneous presence of the decays $h_3 \rightarrow h_2 Z$, $h_2 \rightarrow h_1 Z$, and $h_3 \rightarrow h_1 Z$ violates CP. We say that points in the C2HDM parameter space which lead to this situation belong to class C_1 . Similarly (with the caveat in footnote 1), the simultaneous presence of the decays $h_i \rightarrow h_j Z$, $h_i \rightarrow ZZ$, and $h_j \rightarrow ZZ$, also violates CP. Within the 2HDM, there are three such possibilities, according to the (i, j) assignments, which we name classes C_2 , C_3 , and C_4 . Notice that classes C_1 - C_4 represent CP-violation, regardless of the origin of the neutral scalars. They may come from an N Higgs doublet model, or indeed from scalar fields in any number and from any representation of $SU(2)_L$ (singlets, doublets, triplets, combinations thereof, etc...) In Table 1, we show the decays involved in each class. Furthermore,

Classes	C_1	C_2	C_3	C_4	C_5
Decays	$h_3 \rightarrow h_2 Z$	$h_2 \rightarrow h_1 Z$	$h_3 \rightarrow h_1 Z$	$h_3 \rightarrow h_2 Z$	$h_3 \rightarrow ZZ$
	$h_2 \rightarrow h_1 Z$	$h_1 \rightarrow ZZ$	$h_1 \rightarrow ZZ$	$h_2 \rightarrow ZZ$	$h_2 \rightarrow ZZ$
	$h_3 \rightarrow h_1 Z$	$h_2 \rightarrow ZZ$	$h_3 \rightarrow ZZ$	$h_3 \rightarrow ZZ$	$h_1 \rightarrow ZZ$

Table 1: Classes of combined measurements guaranteed to probe CP-violation in 2HDMs.

in the specific context of a 2HDM, the properties of the fields ensure that, if CP were conserved, there would be two CP even neutral scalars and one CP odd neutral scalar, usually denoted by H , h , and A , respectively. Thus, in the 2HDM, the simultaneous presence of $h_i \rightarrow ZZ$ for $i = 1, 2, 3$ signals CP-violation. We denote that possibility by class C_5 . We stress that class C_5 does not represent necessarily CP-violation in models other than the 2HDM. For example, even with three Higgs doublets one will surely have three neutral scalars and class C_5 would be consistent with CP-conservation. We will further discuss other classes that probe CP-violation that involve one scalar to two scalar decays that usually have the drawback of having smaller cross sections.

It is interesting that there are only three basis-invariant quantities signalling CP-violation in the scalar sector of the 2HDM. They were introduced in [16, 17], the connection with the observables

¹There are CP conserving terms of dimension higher than four that can mediate the decay of a pseudoscalar into two vector bosons. Those could appear at loop level from a fundamental theory, but would lead to rates far smaller than the tree level rates considered in this article. A calculation performed in the framework of the 2HDM has shown [15] that the loop mediated decays of the type $h_i \rightarrow ZZ$ are several orders of magnitude smaller than the tree-level ones.

explained in [14], and revisited in [18]. Measurements of classes C_1 - C_5 are enough to probe all invariants. In the particular setting of the C2HDM, there is only one phase/source of CP-violation, all invariants are related, and the CP-violation in all classes (which one can take as the product of the three rates in each class) is proportional to that phase.

One of the most interesting points of our proposal is that although the above described classes constitute an indisputable sign of CP-violation, they have all been searched for individually at run 1. In fact, the searches $h_i \rightarrow ZZ$ and $h_i \rightarrow h_j Z$ were already performed by both the ATLAS and CMS collaborations. Therefore, as long as we have enough signal events in three of the proposed channels for a given set of parameters, there are good chances of observing direct CP-violation at the next LHC run.

This paper is organized as follows. In section 2, we briefly describe the complex 2HDM and the theoretical and phenomenological constraints imposed on the model with special emphasis on the most recent LHC data. In section 3, we propose a set of CP-violating benchmark points for Type II and for the Flipped model. In the same section we discuss clear signs of CP-violation that involve the decay of one scalar to two scalars. Our conclusions are presented in Section 4. Finally, we present benchmark points for Type I and for the Lepton Specific model in appendix A.

2 The complex two-Higgs doublet model

We use as a benchmark model an extension of the SM with an extra scalar doublet. This complex 2HDM has a softly broken Z_2 symmetry $\phi_1 \rightarrow \phi_1, \phi_2 \rightarrow -\phi_2$ and the scalar potential is written as [5]

$$\begin{aligned} V_H = & m_{11}^2 |\phi_1|^2 + m_{22}^2 |\phi_2|^2 - m_{12}^2 \phi_1^\dagger \phi_2 - (m_{12}^2)^* \phi_2^\dagger \phi_1 \\ & + \frac{\lambda_1}{2} |\phi_1|^4 + \frac{\lambda_2}{2} |\phi_2|^4 + \lambda_3 |\phi_1|^2 |\phi_2|^2 + \lambda_4 (\phi_1^\dagger \phi_2) (\phi_2^\dagger \phi_1) \\ & + \frac{\lambda_5}{2} (\phi_1^\dagger \phi_2)^2 + \frac{\lambda_5^*}{2} (\phi_2^\dagger \phi_1)^2, \end{aligned} \quad (1)$$

and because the potential has to be hermitian, all couplings except m_{12}^2 and λ_5 are real. In order to assure that the two phases cannot be removed simultaneously, we impose $\arg(\lambda_5) \neq 2 \arg(m_{12}^2)$ [13]. By taking m_{12}^2 and λ_5 real we recover the corresponding CP-conserving 2HDM.

The model has three neutral particles with no definite CP, h_1 , h_2 and h_3 , and two charged scalars H^\pm . The mass matrix of the neutral scalar states is obtained via the rotation matrix [19]

$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix} \quad (2)$$

with $s_i = \sin \alpha_i$ and $c_i = \cos \alpha_i$ ($i = 1, 2, 3$) and

$$-\pi/2 < \alpha_1 \leq \pi/2, \quad -\pi/2 < \alpha_2 \leq \pi/2, \quad -\pi/2 \leq \alpha_3 \leq \pi/2. \quad (3)$$

The C2HDM has 9 independent parameters which we choose to be v , $\tan \beta$, m_{H^\pm} , α_1 , α_2 , α_3 , m_1 , m_2 , and $\text{Re}(m_{12}^2)$. With this choice the mass of heavier neutral scalar is a dependent parameter

given by

$$m_3^2 = \frac{m_1^2 R_{13}(R_{12} \tan \beta - R_{11}) + m_2^2 R_{23}(R_{22} \tan \beta - R_{21})}{R_{33}(R_{31} - R_{32} \tan \beta)}. \quad (4)$$

and the parameter space will be restricted to values which obey $m_3 > m_2$.

We will analyse the usual four Yukawa versions of the C2HDM, in which the Z_2 symmetry is extended to the Yukawa Lagrangian [20] in order to avoid flavour changing neutral currents (FCNC). In all models the up-type quarks couple to ϕ_2 and the so-called Type I (Type II) is obtained by coupling down-type quarks and charged leptons to ϕ_2 (ϕ_1), while by coupling the down-type quarks to ϕ_1 and the charged leptons to ϕ_2 we obtain the Flipped model and by coupling the down-type quarks to ϕ_2 and the charged leptons to ϕ_1 we obtain the Lepton Specific model.

We define the signal strength as

$$\mu_f^{h_i} = \frac{\sigma \text{BR}(h_i \rightarrow f)}{\sigma^{\text{SM}} \text{BR}^{\text{SM}}(h_i \rightarrow f)} \quad (5)$$

where σ is the Higgs boson production cross section and $\text{BR}(h_i \rightarrow f)$ is the branching ratio of the h_i decay into the final state f ; σ^{SM} and $\text{BR}^{\text{SM}}(h \rightarrow f)$ are the corresponding quantities calculated in the SM. The cross sections were obtained from: HIGLU [21] - gluon fusion at NNLO, together with the expressions for the CP-violating model in [9]; SusHi [22] - $b\bar{b} \rightarrow h$ at NNLO; [23] - Vh (associated production), $t\bar{t}h$ and $VV \rightarrow h$ (vector boson fusion). The allowed parameter space of the C2HDM was recently reviewed in [10] (see also [6, 9, 13, 19, 24–27]). The benchmark points that clearly signal CP-violation will be presented in the next section and are chosen from this set. The allowed points in parameter space are subject to the constraints we will briefly describe now. We note that we only focus here on scenarios where the lightest scalar h_1 is the 125 GeV Higgs.

- We take the lightest neutral scalar, h_1 , to have a mass of 125 GeV in agreement with the latest results from ATLAS [28] and CMS [29].
- The accuracies in the measurements of the signal strengths in the processes $pp \rightarrow h_1 \rightarrow WW(ZZ)$, $pp \rightarrow h_1 \rightarrow \gamma\gamma$ and $pp \rightarrow h_1 \rightarrow \tau^+\tau^-$ are about 20% at 1σ [29, 30]. As shown in [9], imposing these run 1 constraints guarantees that the C2HDM automatically obeys all other run 1 constraints on the 125 GeV Higgs decays in this model. We will thus force μ_{VV} , $\mu_{\gamma\gamma}$ and $\mu_{\tau\tau}$ to be within 20% of the expected SM value
- The LHC results also allow us to put bounds on the heavier scalars h_2 and h_3 . We impose the results on μ_{VV} [31] in the range [145, 1000] GeV and on $\mu_{\tau\tau}$ [32] in the range [100, 1000] GeV. We also use the results on $h_i \rightarrow ZZ \rightarrow 4l$ from [33] in the range [124, 150] GeV and from [31] in the range [150, 990] GeV, and on $h \rightarrow \gamma\gamma$ from [34, 35]. Finally we also impose the constraints stemming from the results based on the searches $h_i \rightarrow Zh_1 \rightarrow Zb\bar{b}(\tau^+\tau^-)$ [36] and $h_i \rightarrow Zh_1 \rightarrow llb\bar{b}$ [37].
- We consider the constraints on the charged Higgs Yukawa vertices that depend only on the charged Higgs mass and on $\tan \beta$. There is a new bound on $b \rightarrow s\gamma$, in Type II/F [38] of $m_{H^\pm} \geq 480$ GeV at 95% C.L.. Putting together all the constraints from B-physics [39, 40] and also from the $R_b \equiv \Gamma(Z \rightarrow b\bar{b})/\Gamma(Z \rightarrow \text{hadrons})$ [41] measurement, we can state that roughly $\tan \beta \gtrsim 1$ for all models. LEP searches on $e^+e^- \rightarrow H^+H^-$ [42] and the LHC searches on $pp \rightarrow \bar{t}t(\rightarrow H^+\bar{b})$ [43, 44]) lead us to roughly consider $m_{H^\pm} \geq 100$ GeV in Type I/LS.

- We consider the following theoretical constraints: the potential has to be bounded from below [45], perturbative unitarity is required [46–48] and all allowed points comply with the oblique radiative parameters [49–51].
- The scenarios we will present in the next section are a clear signal of CP-violation in models with an extended scalar sector. Models with a CP-violating scalar sector are constrained by bounds from electric dipole moments (EDMs) measurements. Although the search for the proposed final states should be performed from a model independent perspective, we will nevertheless estimate the most important constraints on the CP-violating phases in the context of the C2HDM [7, 52–56].

The most stringent bound [7] comes from the ACME [57] results on the ThO molecule EDM. In order to have points with EDMs of an order of magnitude that conforms to the ACME result, we have computed the Barr-Zee diagrams with fermions in the loop. As we will see, the ACME bound can only be evaded by either going to the limit of the CP-conserving model or in scenarios where cancellations [55, 56] among the neutral scalars occur. These cancellations are due to orthogonality of the R matrix in the case of almost degenerate scalars [9]. We should finally point out that ref. [55] argues that the extraction of the electron EDM from the data is filled with uncertainties and an order of magnitude larger EDM than that claimed by ACME should be allowed for.

3 CP-violating benchmark points

In this section, we present some benchmark points that allow us to definitely probe CP-violation during LHC’s run 2. In table 2, we present four benchmark points, where the first three are for Type II and $P4$ is for the Flipped model (Type I and Lepton Specific are discussed in appendix A). For each point we give the values of the parameters of the model, the values of the pseudoscalar component of the Yukawa coupling of the lightest Higgs and the values of the cross sections for the different processes. The cross sections are calculated assuming that all scalars in the final state are detected in the decay to $b\bar{b}$ and all Z bosons are detected in the leptonic decays, providing therefore a very conservative estimate for the number of signal events available. Regarding the cross sections, we sum over all possible production process with one scalar in the final state. Therefore, the numbers presented in the table correspond either to

$$\sigma(pp \rightarrow h_i + X) BR(h_i \rightarrow h_j Z) BR(h_j \rightarrow b\bar{b}) BR(Z \rightarrow ll), \quad (6)$$

or

$$\sigma(pp \rightarrow h_i + X) BR(h_i \rightarrow ZZ) BR^2(Z \rightarrow ll) \quad (7)$$

and $l = e, \mu$.

The general criteria for the choice of our benchmark points is the following: the points have passed all the constraints described in the previous section; the number of events for a luminosity of $100 fb^{-1}$ should be at least above 50, and the smallest number in table 2 for this luminosity is 61 events. Note that this number already takes into account the decay of the scalar into $b\bar{b}$ and the decay of all Z bosons into leptons (a reduction of 0.06732 for each Z). Therefore, we expect a much larger number of events when all other combinations of final states are taken into account by the

	$P1$	$P2$	$P3$	$P4$
α_1	1.12569	1.04842	-1.33589	1.41610
α_2	0.49091	-0.00825	-0.00129	0.24037
α_3	-1.56775	0.00674	0.63749	-0.81993
β	0.92913	1.00182	1.27669	1.29413
$\tan \beta$	1.33845	1.56366	3.30155	3.52171
m_1 (GeV)	125.00	125.00	125.00	125.00
m_2 (GeV)	127.32	273.15	282.53	231.74
m_3 (GeV)	252.63	421.64	287.80	360.59
m_{H^\pm} (GeV)	481.25	452.50	604.89	527.67
$\text{Re}(m_{12}^2)$ (GeV) ²	-0.5625E+02	0.1183E+05	0.1590E+05	0.2156E+05
b_{D_1}	-0.63099	0.01291	0.00426	-0.83837
b_{L_1}	-0.63099	0.01291	0.00426	0.06760
$C_1[1]$ $\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 Z \rightarrow b\bar{b}l\bar{l})$	114.528 [fb]	61.529 [fb]	0.000 [fb]	27.484 [fb]
$C_1[2]$ $\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 Z \rightarrow b\bar{b}l\bar{l})$	0.000 [fb]	0.615 [fb]	7.401 [fb]	18.462 [fb]
$C_1[3]$ $\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 Z \rightarrow b\bar{b}l\bar{l})$	26.656 [fb]	1.100 [fb]	24.519 [fb]	1.787 [fb]
$C_2[1]$ $\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 Z \rightarrow b\bar{b}l\bar{l})$	0.000 [fb]	0.615 [fb]	7.401 [fb]	18.462 [fb]
$C_2[2]$ $\sigma_1 \times \text{BR}(h_1 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	5.495 [fb]	5.792 [fb]	5.592 [fb]	4.802 [fb]
$C_2[3]$ $\sigma_2 \times \text{BR}(h_2 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	1.386 [fb]	2.598 [fb]	1.802 [fb]	1.220 [fb]
$C_3[1]$ $\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 Z \rightarrow b\bar{b}l\bar{l})$	26.656 [fb]	1.100 [fb]	24.519 [fb]	1.787 [fb]
$C_3[2]$ $\sigma_1 \times \text{BR}(h_1 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	5.495 [fb]	5.792 [fb]	5.592 [fb]	4.802 [fb]
$C_3[3]$ $\sigma_3 \times \text{BR}(h_3 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	1.011 [fb]	0.003 [fb]	1.733 [fb]	1.058 [fb]
$C_4[1]$ $\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 Z \rightarrow b\bar{b}l\bar{l})$	114.528 [fb]	61.529 [fb]	0.000 [fb]	27.484 [fb]
$C_4[2]$ $\sigma_2 \times \text{BR}(h_2 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	1.386 [fb]	2.598 [fb]	1.802 [fb]	1.220 [fb]
$C_4[3]$ $\sigma_3 \times \text{BR}(h_3 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	1.011 [fb]	0.003 [fb]	1.733 [fb]	1.058 [fb]
$C_5[1]$ $\sigma_3 \times \text{BR}(h_3 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	1.011 [fb]	0.003 [fb]	1.733 [fb]	1.058 [fb]
$C_5[2]$ $\sigma_2 \times \text{BR}(h_2 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	1.386 [fb]	2.598 [fb]	1.802 [fb]	1.220 [fb]
$C_5[3]$ $\sigma_1 \times \text{BR}(h_1 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	5.495 [fb]	5.792 [fb]	5.592 [fb]	4.802 [fb]

Table 2: Benchmark points for Type II: $P1$, $P2$ and $P3$, and for the Flipped model: $P4$, for LHC at $\sqrt{s} = 13$ TeV. All Z bosons decay leptonically which corresponds to a factor of 0.06732 for each Z decay.

experiments (as it is obviously the case for the ZZ final states, where we can have combinations of leptons and jets final states). In table 3 we show the rates obtained for the benchmark points which are then compared to the available experimental data from the LHC at $\sqrt{s} = 8$ TeV.

The criteria for the choice of each particular point is severely constrained by the ACME results. In fact, all the points have similar features in that they either have two neutral scalar masses almost degenerate or values of the angles very close to zero (therefore approaching the limit of the CP-conserving 2HDM). Points $P1$ and $P3$ have degenerate masses while point $P2$ has very small α_2 and α_3 values. That is why for point $P2$, the decay $h_2 \rightarrow h_1 Z$ is suppressed. In the limit $\alpha_2 = \alpha_3 = 0$, h_3 is the pseudo-scalar and h_1 and h_2 are scalars and $h_2 \rightarrow h_1 Z$ is forbidden. For the same reason, $h_3 \rightarrow ZZ$ is forbidden. Note however that although α_2 and α_3 are very small we still have a large number of signal events for 100 fb^{-1} in $h_2 \rightarrow h_1 Z$. As $\alpha_{2,3}$ move away from zero (the CP-conserving limit) certain CP-violating observables grow extremely fast. Thus, we can be very close to this limit and still have large CP-violating signals.

The points were also chosen so that they would probe more than one class simultaneously. $P1$ probes classes C_3 , C_4 and C_5 ; $P2$ probes C_1 and C_2 ; $P3$ probes C_2 , C_3 and C_5 while the point for

	$P1$	$P2$	$P3$	$P4$
$\mu_{WW}(h_1) = \mu_{ZZ}(h_1)$	1.09016	1.14962	1.11696	0.95402
$\mu_{\tau\tau}(h_1)$	1.16717	0.98826	0.96621	1.02628
$\mu_{\gamma\gamma}(h_1)$	0.92139	1.02589	0.87922	0.85345
$\mu_{bb(VH)}(h_1)$	0.71662	0.93593	0.65922	0.94294
$\mu_{WW}(h_2)/\mu_{WW}^{\text{exp}}$	0.225/NA	0.151/0.185	0.117/0.170	0.058/0.121
$\mu_{ZZ}(h_2)/\mu_{ZZ}^{\text{exp}}$	0.225/1.264	0.151/0.190	0.117/0.176	0.058/0.130
$\mu_{\tau\tau}(h_2)/\mu_{\tau\tau}^{\text{exp}}$	1.59/ 3.98	180.00/ 472.37	7.98/ 490.42	0.90/ 363.88
$\sigma BR_{\gamma\gamma}(h_2)/\sigma BR_{\gamma\gamma}^{\text{exp}}$ [fb]	15.265/ 29.705	0.318/2.678	0.011/2.727	0.018/5.998
$\mu_{\gamma\gamma}(h_2)/\mu_{\gamma\gamma}^{\text{exp}}$ ($m < 150\text{GeV}$)	0.258/0.259	0.000/0.000	0.000/0.000	0.000/0.000
$\sigma BR_{Zh \rightarrow Zbb}(h_2)/\sigma BR_{Zh \rightarrow Zbb}^{\text{exp}}$ [pb]	0.000/ 0.000	0.003/0.308	0.042/0.250	0.108/0.403
$\sigma BR_{Zh \rightarrow Z\tau\tau}(h_2)/\sigma BR_{Zh \rightarrow Z\tau\tau}^{\text{exp}}$ [pb]	0.000/ 0.000	0.000/0.105	0.005/0.089	0.012/0.085
$\sigma BR_{Zh \rightarrow llbb}(h_2)/\sigma BR_{Zh \rightarrow llbb}^{\text{exp}}$ [fb]	0.000/0.000	0.222/ 15.242	2.855/ 12.167	7.259/ 14.082
$\mu_{WW}(h_3)/\mu_{WW}^{\text{exp}}$	0.053/0.074	0.000/0.083	0.111/0.125	0.072/0.099
$\mu_{ZZ}(h_3)/\mu_{ZZ}^{\text{exp}}$	0.053/0.068	0.000/0.086	0.111/0.147	0.072/0.095
$\mu_{\tau\tau}(h_3)/\mu_{\tau\tau}^{\text{exp}}$	3.12/ 427.59	8.70/ 1241.83	13.52/ 500.43	0.04/ 663.64
$\sigma BR_{\gamma\gamma}(h_3)/\sigma BR_{\gamma\gamma}^{\text{exp}}$ [fb]	0.022/6.511	0.028/2.002	0.010/2.672	0.004/2.823
$\sigma BR_{Zh \rightarrow Zbb}(h_3)/\sigma BR_{Zh \rightarrow Zbb}^{\text{exp}}$ [pb]	0.147/0.310	0.005/0.081	0.135/0.228	0.009/0.156
$\sigma BR_{Zh \rightarrow Z\tau\tau}(h_3)/\sigma BR_{Zh \rightarrow Z\tau\tau}^{\text{exp}}$ [pb]	0.017/0.102	0.001/0.035	0.016/0.081	0.001/0.038
$\sigma BR_{Zh \rightarrow llbb}(h_3)/\sigma BR_{Zh \rightarrow llbb}^{\text{exp}}$ [fb]	9.926/ 23.839	0.337/2.731	9.076/ 15.230	0.605/7.358

Table 3: Constraints from the LHC at $\sqrt{s} = 8$ TeV for the benchmark points $P1$, $P2$ and $P3$ (Type II) and $P4$ (Flipped). NA stands for not available.

the Flipped model probes all classes. Furthermore, points $P1$ and $P4$ were also chosen to show that large pseudoscalar components are not only still allowed, as previously discussed in [10], but they can also easily be probed at the next LHC run.

Finally, in table 4 we present the production cross sections for h_1 , h_2 and h_3 . In the same table we show the $\sigma(h_i) \times Br(h_i \rightarrow X)$ where X stands for the main final states being searched by ATLAS and CMS at the next LHC run. These numbers allow the experimental groups to understand if a given scalar is found in direct production whether it comes from a CP-violating process or not. In the same table we also present the values of the scalar production cross sections that lead to decays of the type $h_i \rightarrow h_j h_k$ and $h_i \rightarrow h_j h_k$ and that are clearly too small to be detected at the LHC for the sets of benchmark chosen, except for a few cases for points $P1$ and $P4$.

3.1 CP-violating scenarios involving scalar to two scalars decays

There are other classes of decays that constitute a sign of CP-violation in the 2HDM. Some of them involve the decay $h_3 \rightarrow h_2 h_1$ which is not present in the CP-conserving version of the 2HDM. In fact the decay $h_3 \rightarrow h_2 h_1$ is only possible if either all h_i are CP-even, two of the h_i are CP-odd and one is CP-even or if CP is not conserved. Since the decay $h_1 \rightarrow ZZ$ was already observed we know h_1 has a CP-even component. Therefore, we can discuss the combinations of decays that together with $h_3 \rightarrow h_2 h_1$ will be a clear sign of CP-violation in the 2HDM or that will point to other extensions of the SM that can be either CP-conserving or CP-violating.

In table 5 we present new classes of decays that again constitute model independent signs of CP-violation. Class C_6 is composed by the three decays $h_1 \rightarrow ZZ$, $h_3 \rightarrow h_2 h_1$ and $h_3 \rightarrow h_2 Z$. There are other sets of simultaneous measurements involving $h_3 \rightarrow h_2 h_1$ that are consistent with

	$P1$	$P2$	$P3$	$P4$
$\sigma(h_1)$ 13TeV	61.600 [pb]	53.217 [pb]	54.825 [pb]	51.275 [pb]
$\sigma(h_1)\text{BR}(h_1 \rightarrow W^*W^*)$	11.819 [pb]	12.459 [pb]	12.028 [pb]	10.328 [pb]
$\sigma(h_1)\text{BR}(h_1 \rightarrow Z^*Z^*)$	1.212 [pb]	1.278 [pb]	1.234 [pb]	1.060 [pb]
$\sigma(h_1)\text{BR}(h_1 \rightarrow bb)$	34.383 [pb]	29.087 [pb]	28.256 [pb]	30.313 [pb]
$\sigma(h_1)\text{BR}(h_1 \rightarrow \tau\tau)$	3.969 [pb]	3.360 [pb]	3.264 [pb]	3.485 [pb]
$\sigma(h_1)\text{BR}(h_1 \rightarrow \gamma\gamma)$	129.973 [fb]	144.664 [fb]	123.188 [fb]	120.222 [fb]
$\sigma_2 \equiv \sigma(h_2)$ 13TeV	56.583 [pb]	4.262 [pb]	1.602 [pb]	3.354 [pb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow WW)$	2.814 [pb]	1.323 [pb]	0.910 [pb]	0.656 [pb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow ZZ)$	0.306 [pb]	0.573 [pb]	0.398 [pb]	0.269 [pb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow bb)$	42.534 [pb]	1.894 [pb]	0.067 [pb]	1.944 [pb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow \tau\tau)$	4.911 [pb]	0.224 [pb]	0.008 [pb]	0.002 [pb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow \gamma\gamma)$	35.041 [fb]	0.879 [fb]	0.027 [fb]	0.046 [fb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 Z)$	0.000 [pb]	0.017 [pb]	0.213 [pb]	0.464 [pb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 Z \rightarrow bb Z)$	0.000 [pb]	0.009 [pb]	0.110 [pb]	0.274 [pb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 Z \rightarrow \tau\tau Z)$	0.000 [fb]	1.055 [fb]	12.697 [fb]	31.530 [fb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 h_1)$	0.000 [fb]	0.007 [fb]	5.016 [fb]	0.000 [fb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 h_1 \rightarrow bb bb)$	0.000 [fb]	0.002 [fb]	1.332 [fb]	0.000 [fb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 h_1 \rightarrow bb \tau\tau)$	0.000 [fb]	0.000 [fb]	0.308 [fb]	0.000 [fb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 h_1 \rightarrow \tau\tau \tau\tau)$	0.000 [fb]	0.000 [fb]	0.018 [fb]	0.000 [fb]
$\sigma_3 \equiv \sigma(h_3)$ 13TeV	4.043 [pb]	8.480 [pb]	2.086 [pb]	1.819 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow WW)$	0.526 [pb]	0.001 [pb]	0.871 [pb]	0.509 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow ZZ)$	0.223 [pb]	0.001 [pb]	0.382 [pb]	0.233 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow bb)$	0.047 [pb]	0.016 [pb]	0.109 [pb]	0.058 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow \tau\tau)$	5.558 [fb]	1.913 [fb]	12.856 [fb]	0.020 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow \gamma\gamma)$	0.059 [fb]	0.093 [fb]	0.028 [fb]	0.013 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 Z)$	0.709 [pb]	0.030 [pb]	0.707 [pb]	0.045 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 Z \rightarrow bb Z)$	0.396 [pb]	0.016 [pb]	0.364 [pb]	0.027 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 Z \rightarrow \tau\tau Z)$	45.708 [fb]	1.887 [fb]	42.067 [fb]	3.051 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 Z)$	2.263 [pb]	2.057 [pb]	0.000 [pb]	0.705 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 Z \rightarrow bb Z)$	1.701 [pb]	0.914 [pb]	0.000 [pb]	0.408 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 Z \rightarrow \tau\tau Z)$	196.416 [fb]	107.996 [fb]	0.000 [fb]	0.500 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 h_1)$	0.090 [fb]	0.230 [fb]	2.071 [fb]	19.918 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 h_1 \rightarrow bb bb)$	0.028 [fb]	0.069 [fb]	0.550 [fb]	6.961 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 h_1 \rightarrow bb \tau\tau)$	0.007 [fb]	0.016 [fb]	0.127 [fb]	1.601 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 h_1 \rightarrow \tau\tau \tau\tau)$	0.000 [fb]	0.001 [fb]	0.007 [fb]	0.092 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 h_1)$	263.916 [fb]	0.038 [fb]	0.000 [fb]	11.157 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 h_1 \rightarrow bb bb)$	110.732 [fb]	0.009 [fb]	0.000 [fb]	3.822 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 h_1 \rightarrow bb \tau\tau)$	25.567 [fb]	0.002 [fb]	0.000 [fb]	0.444 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 h_1 \rightarrow \tau\tau \tau\tau)$	1.476 [fb]	0.000 [fb]	0.000 [fb]	0.001 [fb]

Table 4: Predictions for $\sigma \times \text{BR}$ for the LHC at $\sqrt{s} = 13$ TeV for the benchmark points $P1$, $P2$ and $P3$ (Type II) and $P4$ (Flipped).

CP conservation in models with more than two Higgs doublets, and which allow the determination of the possible CP assignments. These are:

- $[h_1 \rightarrow ZZ; h_3 \rightarrow h_2 h_1] h_3 \rightarrow h_1 Z$, leading to the CP assignments $(+, -, -)$;

- $[h_1 \rightarrow ZZ; h_3 \rightarrow h_2 h_1] h_2 \rightarrow h_1 Z$, leading to the CP assignments $(+, -, -)$;
- $[h_1 \rightarrow ZZ; h_3 \rightarrow h_2 h_1] h_2 \rightarrow ZZ$, leading to the CP assignments $(+, +, +)$.

There are still other combinations involving scalar to scalar decays that are model independent signs of CP-violation. Such is the case of class C_7 in table 5 composed by the decays $h_{2,3} \rightarrow h_1 h_1$, $h_{2,3} \rightarrow h_1 Z$ and $h_1 \rightarrow ZZ$. Finally, other combinations like $h_3 \rightarrow h_1 h_1 (h_2 h_2)$, $h_2 \rightarrow h_1 h_1$ and $h_1 \rightarrow ZZ$ are not possible in a CP-conserving 2HDM but are possible in the C2HDM and can also serve to determine the CP-quantum numbers of other extensions of the scalar sector. A detailed study of these classes will be performed in a forthcoming publication [58].

Classes	C_6	C_7
Decays	$h_3 \rightarrow h_2 h_1$	$h_{2,3} \rightarrow h_1 h_1$
	$h_3 \rightarrow h_2 Z$	$h_{2,3} \rightarrow h_1 Z$
	$h_1 \rightarrow ZZ$	$h_1 \rightarrow ZZ$

Table 5: Classes of combined measurements guaranteed to probe CP-violation.

4 Conclusions

We have proposed five classes of processes that constitute conclusive evidence of CP-violation in scalar decays. While the C_5 class is particular to the C2HDM, all other classes are valid in any scalar extension of the SM. One of the most attractive features of our proposal is to rely on searches that are already planned for the LHC run 2, namely $h_i \rightarrow ZZ$ and $h_i \rightarrow h_j Z$. Furthermore, it does not depend on complex distributions nor asymmetries of any kind, but only on total rates of specific processes. It is a direct and straightforward way to search for CP-violation at the LHC in scalar decays. As far as we know this is the only method of probing CP-violation based on rates only.

We have shown that even taking into account all constraints and in particular the one from ACME that heavily restricts the amount of CP-violation in the model, it is still easy to find points to probe each of the proposed classes. In many cases a point can be used to probe several classes simultaneously. We have chosen a set of benchmark points according to different criteria, always keeping in mind that the decays should be within the reach of the LHC's run 2. We should point out however that even if these points are excluded the parameter space is large enough to provide many more points and the model is far from excluded (nor is CP-violation in scalar decays excluded). The future bounds on EDMs [52, 59] can have a strong impact on the allowed parameter space, and one has to consider the interplay between the EDM bounds and the data from run 2 to propose scenarios for future experiments. However, the EDM constraints get looser if one goes beyond the setting discussed here, allowing for $\lambda_6 \neq 0$ and/or $\lambda_7 \neq 0$ [11]. In that case classes C_1 to C_5 still probe CP-violation, and thus the methods proposed here should be pursued experimentally regardless of the fate of the C2HDM. In particular, classes C_1 to C_4 probe CP-violation in all models.

We also propose two new classes of decays, C_6 and C_7 that involve the already observed decay $h_1 \rightarrow ZZ$, one decay of the type $h_i \rightarrow h_j h_{j(k)}$ with $j \neq k$ and one decay of type $h_j \rightarrow h_k Z$.

As important guidelines for experiments, we propose six benchmark points covering all C2HDM types: type II ($P1$ - $P3$), and Flipped ($P4$) in tables 2, 3 and 4; type I ($P5$) and Lepton Specific

($P6$) in tables 6, 7 and 8 of appendix A. We provide all event rates for all scalar processes and for each benchmark points. This allows not only to search for the CP-violating classes of decays but also to confirm or disprove the points via direct search of each scalar. If a particular point is found the other decays could clarify if we are in presence of the C2HDM or of some other CP-violating extension of the SM.

A Benchmark points for Type I and for the Lepton Specific models

	$P5$	$P6$
α_1	1.30680	1.08742
α_2	0.10867	0.00960
α_3	-0.20624	-0.41962
β	1.15333	1.03051
$\tan \beta$	2.25459	1.66717
m_1 (GeV)	125.00	125.00
m_2 (GeV)	235.45	262.98
m_3 (GeV)	359.20	264.60
m_{H^\pm} (GeV)	522.87	471.76
$\text{Re}(m_{12}^2)$ (GeV) ²	0.9504E+02	-0.3006E+05
b_{D_1}	0.04810	0.00576
b_{L_1}	0.04810	-0.01600
$C_1[1] \sigma_3 \times \text{BR}(h_3 \rightarrow h_2 Z \rightarrow b\bar{b}l\bar{l})$	1.251 [fb]	0.000 [fb]
$C_1[2] \sigma_2 \times \text{BR}(h_2 \rightarrow h_1 Z \rightarrow b\bar{b}l\bar{l})$	5.644 [fb]	3.030 [fb]
$C_1[3] \sigma_3 \times \text{BR}(h_3 \rightarrow h_1 Z \rightarrow b\bar{b}l\bar{l})$	15.477 [fb]	27.984 [fb]
$C_2[1] \sigma_2 \times \text{BR}(h_2 \rightarrow h_1 Z \rightarrow b\bar{b}l\bar{l})$	5.644 [fb]	3.030 [fb]
$C_2[2] \sigma_1 \times \text{BR}(h_1 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	4.954 [fb]	5.146 [fb]
$C_2[3] \sigma_2 \times \text{BR}(h_2 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	1.934 [fb]	1.053 [fb]
$C_3[1] \sigma_3 \times \text{BR}(h_3 \rightarrow h_1 Z \rightarrow b\bar{b}l\bar{l})$	15.477 [fb]	27.984 [fb]
$C_3[2] \sigma_1 \times \text{BR}(h_1 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	4.954 [fb]	5.146 [fb]
$C_3[3] \sigma_3 \times \text{BR}(h_3 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	1.326 [fb]	1.840 [fb]
$C_4[1] \sigma_3 \times \text{BR}(h_3 \rightarrow h_2 Z \rightarrow b\bar{b}l\bar{l})$	1.251 [fb]	0.000 [fb]
$C_4[2] \sigma_2 \times \text{BR}(h_2 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	1.934 [fb]	1.053 [fb]
$C_4[3] \sigma_3 \times \text{BR}(h_3 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	1.326 [fb]	1.840 [fb]
$C_5[1] \sigma_3 \times \text{BR}(h_3 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	1.326 [fb]	1.840 [fb]
$C_5[2] \sigma_2 \times \text{BR}(h_2 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	1.934 [fb]	1.053 [fb]
$C_5[3] \sigma_1 \times \text{BR}(h_1 \rightarrow ZZ \rightarrow l\bar{l}l\bar{l})$	4.954 [fb]	5.146 [fb]

Table 6: Benchmark points for Type I: $P5$ and for the Lepton Specific model: $P6$, for LHC at $\sqrt{s} = 13$ TeV. All Z decay leptonically corresponding to a factor of 0.06732.

In this appendix we present two further benchmark points, one for Type I and the other for the Lepton Specific (LS) model. In table 6 we present the values of the parameters and the cross sections for benchmark point $P5$ in Type I and $P6$ for the LS model. In Type I it was possible to find a point that not only complies with all the constraints but that probes all CP-violating classes at the same time. For the LS model the classes probed are C_2 , C_3 and C_5 .

As we did for the remaining benchmark points, we present in table 7 the effect of the LHC constraints on the processes involving scalars. In table 8 we present the production cross sections

	$P5$	$P6$
$\mu_{WW}(h_1) = \mu_{ZZ}(h_1)$	0.98240	1.02070
$\mu_{\tau\tau}(h_1)$	1.12419	0.83628
$\mu_{\gamma\gamma}(h_1)$	0.84875	0.86872
$\mu_{bb(VH)}(h_1)$	0.99480	1.02881
$\mu_{WW}(h_2)/\mu_{WW}^{\text{exp}}$	0.091/0.115	0.058/0.108
$\mu_{ZZ}(h_2)/\mu_{ZZ}^{\text{exp}}$	0.091/0.111	0.058/0.112
$\mu_{\tau\tau}(h_2)/\mu_{\tau\tau}^{\text{exp}}$	0.56/ 377.80	72.97/ 451.42
$\sigma BR_{\gamma\gamma}(h_2)/\sigma BR_{\gamma\gamma}^{\text{exp}}$ [fb]	0.046/3.975	0.125/6.838
$\mu_{\gamma\gamma}(h_2)/\mu_{\gamma\gamma}^{\text{exp}}$ ($m < 150\text{GeV}$)	0.000/0.000	0.000/0.000
$\sigma BR_{Zh \rightarrow Zbb}(h_2)/\sigma BR_{Zh \rightarrow Zbb}^{\text{exp}}$ [pb]	0.032/0.337	0.016/0.349
$\sigma BR_{Zh \rightarrow Z\tau\tau}(h_2)/\sigma BR_{Zh \rightarrow Z\tau\tau}^{\text{exp}}$ [pb]	0.004/0.080	0.001/0.114
$\sigma BR_{Zh \rightarrow llbb}(h_2)/\sigma BR_{Zh \rightarrow llbb}^{\text{exp}}$ [fb]	2.127/ 13.013	1.100/ 27.341
$\mu_{WW}(h_3)/\mu_{WW}^{\text{exp}}$	0.087/0.097	0.102/0.113
$\mu_{ZZ}(h_3)/\mu_{ZZ}^{\text{exp}}$	0.087/0.094	0.102/0.123
$\mu_{\tau\tau}(h_3)/\mu_{\tau\tau}^{\text{exp}}$	0.89/ 656.23	281.79/ 454.89
$\sigma BR_{\gamma\gamma}(h_3)/\sigma BR_{\gamma\gamma}^{\text{exp}}$ [fb]	0.046/2.758	0.875/6.334
$\sigma BR_{Zh \rightarrow Zbb}(h_3)/\sigma BR_{Zh \rightarrow Zbb}^{\text{exp}}$ [pb]	0.075/0.155	0.151/0.348
$\sigma BR_{Zh \rightarrow Z\tau\tau}(h_3)/\sigma BR_{Zh \rightarrow Z\tau\tau}^{\text{exp}}$ [pb]	0.009/0.038	0.013/0.114
$\sigma BR_{Zh \rightarrow llbb}(h_3)/\sigma BR_{Zh \rightarrow llbb}^{\text{exp}}$ [fb]	5.077/7.483	10.163/ 24.919

Table 7: Constraints from the LHC at $\sqrt{s} = 8$ TeV for the benchmark points $P5$ (Type I) and $P6$ (Lepton Specific).

for h_1 , h_2 and h_3 and also the $\sigma(h_i) \times Br(h_i \rightarrow X)$ where again X stands for the most relevant final states searched by ATLAS and CMS at the next LHC run. We also show the values of the scalar production cross sections that lead to decays of the type $h_i \rightarrow h_j h_j$ and $h_i \rightarrow h_j h_k$. Interestingly, for the benchmark points of Type I and Lepton Specific, there are many scalar to scalar decays that could be probed at the next LHC run.

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	$P5$	$P6$
$\sigma(h_1)$ 13TeV	55.144 [pb]	53.455 [pb]
$\sigma(h_1)\text{BR}(h_1 \rightarrow W^*W^*)$	10.657 [pb]	11.069 [pb]
$\sigma(h_1)\text{BR}(h_1 \rightarrow Z^*Z^*)$	1.093 [pb]	1.136 [pb]
$\sigma(h_1)\text{BR}(h_1 \rightarrow bb)$	33.118 [pb]	32.152 [pb]
$\sigma(h_1)\text{BR}(h_1 \rightarrow \tau\tau)$	3.825 [pb]	2.845 [pb]
$\sigma(h_1)\text{BR}(h_1 \rightarrow \gamma\gamma)$	119.794 [fb]	122.579 [fb]
$\sigma_2 \equiv \sigma(h_2)$ 13TeV	1.620 [pb]	4.920 [pb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow WW)$	1.032 [pb]	0.542 [pb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow ZZ)$	0.427 [pb]	0.232 [pb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow bb)$	0.012 [pb]	0.097 [pb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow \tau\tau)$	0.001 [pb]	0.109 [pb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow \gamma\gamma)$	0.123 [fb]	0.344 [fb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 Z)$	0.140 [pb]	0.075 [pb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 Z \rightarrow bb Z)$	0.084 [pb]	0.045 [pb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 Z \rightarrow \tau\tau Z)$	9.683 [fb]	3.982 [fb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 h_1)$	0.000 [fb]	3772.577 [fb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 h_1 \rightarrow bb bb)$	0.000 [fb]	1364.787 [fb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 h_1 \rightarrow bb \tau\tau)$	0.000 [fb]	241.505 [fb]
$\sigma_2 \times \text{BR}(h_2 \rightarrow h_1 h_1 \rightarrow \tau\tau \tau\tau)$	0.000 [fb]	10.684 [fb]
$\sigma_3 \equiv \sigma(h_3)$ 13TeV	9.442 [pb]	10.525 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow WW)$	0.638 [pb]	0.945 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow ZZ)$	0.293 [pb]	0.406 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow bb)$	0.004 [pb]	0.422 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow \tau\tau)$	0.432 [fb]	407.337 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow \gamma\gamma)$	0.140 [fb]	2.410 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 Z)$	0.383 [pb]	0.691 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 Z \rightarrow bb Z)$	0.230 [pb]	0.416 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 Z \rightarrow \tau\tau Z)$	26.554 [fb]	36.779 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 Z)$	2.495 [pb]	0.000 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 Z \rightarrow bb Z)$	0.019 [pb]	0.000 [pb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 Z \rightarrow \tau\tau Z)$	2.188 [fb]	0.000 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 h_1)$	433.402 [fb]	6893.255 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 h_1 \rightarrow bb bb)$	156.329 [fb]	2493.740 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 h_1 \rightarrow bb \tau\tau)$	36.111 [fb]	441.277 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_1 h_1 \rightarrow \tau\tau \tau\tau)$	2.085 [fb]	19.521 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 h_1)$	0.000 [fb]	0.000 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 h_1 \rightarrow bb bb)$	0.000 [fb]	0.000 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 h_1 \rightarrow bb \tau\tau)$	0.000 [fb]	0.000 [fb]
$\sigma_3 \times \text{BR}(h_3 \rightarrow h_2 h_1 \rightarrow \tau\tau \tau\tau)$	0.000 [fb]	0.000 [fb]

Table 8: Predictions for $\sigma \times \text{BR}$ at $\sqrt{s} = 13$ TeV for the benchmark points $P5$ (Type I) and $P6$ (Lepton Specific).

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